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What is the impact of COVID-19 pandemic on global carbon emissions?

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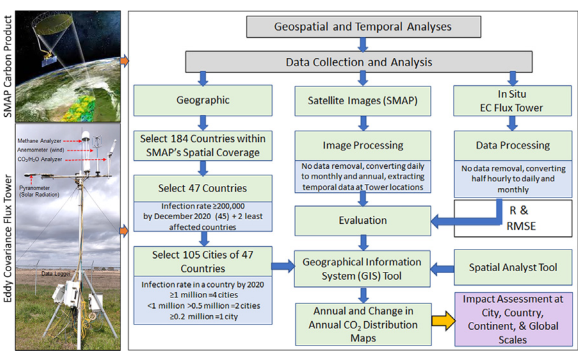
HIGHLIGHTS

- Significant effects of lockdown measures on annual CO_2 emissions globally
- Quantifying annual CO_2 emissions is vital to understand the impact of pandemic.
- Reduction in carbon emissions during the pandemic is temporary and not sustainable.
- Carbon emissions of select 184 countries reduced by 438 Mt in 2020 than in 2019.

GRAPHICAL ABSTRACT



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ABSTRACT

The coronavirus 2019 (COVID 19, or SARS-CoV-2) pandemic that started in December 2019 has caused an unprecedented impact in most countries globally and continues to threaten human lives worldwide. The COVID-19 and strict lockdown measures have had adverse effects on human health and national economies. These lockdown measures have played a critical role in improving air quality, water quality, and the ozone layer and reducing greenhouse gas emissions. Using Soil Moisture Active Passive (SMAP) Level 4 carbon (SMAP LC4) satellite products, this study investigated the impacts of COVID-19 lockdown measures on annual carbon emissions globally, focusing on 47 greatly affected countries and their 105 cities by December 2020. It is shown that while the lockdown measures significantly reduced carbon emissions globally, several countries and cities observed this reduction as temporary because strict lockdown measures were not imposed for extended periods in 2020. Overall, the total carbon emissions of select 184 countries reduced by 438 Mt in 2020 than in 2019. Since the global economic activities are slowly expected to return to the non-COVID-19 state, the reduction in carbon emissions during the pandemic will not be sustainable in the long run. For sustainability, concerned authorities have to put significant efforts to change transportation, climate, and environmental policies globally that fuel carbon emissions. Overall, the presented results provide directions to the stakeholders and policymakers to develop and implement measures to control carbon emissions for a sustainable environment.

1. Introduction

The coronavirus 2019 (COVID 19, or SARS-CoV-2) pandemic started in December 2019, regarded as a form of pneumonia, in Wuhan city, Hubei Province, China (Gautam, 2020; Huang et al., 2020; Ju et al.,

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2021; Rume and Islam, 2020). Within a year as of December 2020, over 81.5 million cases had been reported globally in 223 countries, including sovereign, dependent territories, and self-declared nations (WHO, 2021).

On March 11, 2020, the WHO declared the COVID-19 outbreak a global pandemic. The pandemic necessitated aggressive combating strategies via social distancing, wearing face masks, and stringent lockdowns in many cities across the world. The lockdowns led to a complete or partial halt in economic, physical, and social activities but had a positive outlook on air quality, environment, and greenhouse gases (GHGs), including CO_2 emissions (Naderipour et al., 2020).

GHGs, including CO_2 emissions, are rapidly increasing, and Earth's climate is continuously warming (Anderson et al., 2016; de Larminat, 2016; El Geneidy et al., 2021; Solomon et al., 2009). Vegetated land surfaces play a significant role in controlling the carbon dynamics in the global carbon cycle; however, knowledge about the comprehensive role of the terrestrial biosphere on a regional to global scale under changing climate is still limited (Ray et al., 2020; Stauch et al., 2008). It is an opportunity for everyone, including policymakers, to develop and implement strategies to reduce GHGs emissions, including CO_2, one of the rapidly increasing GHGs on the Earth. It is the perfect time to learn non-lockdown measures strategies implemented during COVID-19 and implement them to curb global carbon emissions and mitigate climate change impact in the long run (Nguyen et al., 2021).

There have recently been investigations into the impact of COVID-19 on the environment during 2020 and pre-COVID periods, relatively for a short duration (a few weeks to a few months of COVID and non-COVID periods). These studies could, however, have missed including the effects of activities not directly related to COVID-19, such as meteorological conditions and seasonality, which might not be the same in two different years during the same period as well as in two different geographical locations. For example, Liu et al. (2020) found that the first months of 2020 were exceptionally warm across much of the northern hemisphere than in the same period in 2019, which caused lower CO_2 emissions in 2020 than in 2019 when no external forces, such as COVID-19, were present. In addition, the COVID-19 lockdown measures could have both positive and negative indirect effects on the environment. Focusing on China, the US, Italy, and Spain, Zambrano-Monserrate et al. (2020) dealt with the indirect positive and negative effects of the COVID-19 pandemic on the environment. While a significant association between improvement in air quality and lockdown measures was found, they also noted the indirect negative effects caused by the reduction in waste recycling, increase in waste, and contamination of land, water, and air during the lockdown measures. It was concluded that the decrease in GHG emissions currently observed by some countries was only temporary, and a significant increase in emissions would be possible once the pandemic ended or lockdown measures were lifted (Filonchyk et al., 2020; Le Quéré et al., 2020).

During the COVID-19 pandemic, different forms of lockdown measures, city to national level, were implemented to control the spread of COVID-19. While lockdown measures limited transportation, agricultural, industrial, and manufacturing activities, causing negative impacts on socio-economic activities, it positively impacted the environment (Hoang et al., 2021a; Le et al., 2020). Several researchers studied the effect of the COVID-19 pandemic on air quality parameters, such as particulate matter (PM2.5/PM10), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and aerosol optical depth (AOD) in the period before the pandemic and during the implementation of preventive measures to control COVID-19 (Balasubramaniam et al., 2020; Baldasano, 2020; Chekir and Ben Salem, 2021; Chen et al., 2020; Gulabchandani and Sethi, 2020; Gupta et al., 2020; Ju et al., 2021; Kumari and Toshniwal, 2020; Liu et al., 2021; Mahato and Ghosh, 2020; Singh et al., 2020). The researchers primarily compared air quality data measured during the pandemic with data obtained in the same period of 2019, and found a reduction in most air pollutants and an increase in ozone in 2020 compared to the same duration in 2019. Consequently, a significant improvement in air quality because of potential measures implemented during the pandemic was reported (Saadat et al., 2020).

Most of the studies that investigated the impact of COVID-19 on air quality considered only a few cities or countries globally, perhaps due to the lack of global in-situ data. While the bulk of studies used in-situ measurements alone (Adams, 2020; Baldasano, 2020; Bao and Zhang, 2020; Dantas et al., 2020; Kerimray et al., 2020) or in combination with modeled data (Griffin et al., 2020; Griffith et al., 2020; He et al., 2020; Li et al., 2020; Mollalo et al., 2020; Perera et al., 2021), some studies did use remotely sensed data to investigate the impact of lockdown measures on the environment at local, regional, national, and global scales (Filippini et al., 2020; Filonchyk et al., 2020; Mendez-Espinosa et al., 2020; Metya et al., 2020; Mostafa et al., 2021). Satellite observations can help identify air pollutants and GHG emissions globally (Griffin et al., 2020). For example, Pei et al. (2020) used remotely sensed (e.g., TROPOspheric Monitoring Instrument (TRPOMI), Sentinel-5, and Ozone Monitoring Instrument (OMI) and in-situ data), Zheng et al. (2020a, b) used TROPOMI satellite data to investigate the impacts of COVID-19-related lockdown measures on different air pollutants in different regions of China. They found a significant impact of lockdown measures on the reduction in the NO_2 concentration but no improvement in the overall air quality in China's urban areas. Using Sentinel-5P and the Himawari-8 satellites data to examine the concentrations of NO_2, HCHO, SO_2, and CO and the AOD in East Asia in February 2019 and 2020, Ghahremanloo et al. (2021) found significant reductions in pollutants in Wuhan, China, in February 2020 compared to February 2019. However, they found decreases in all selected pollutants in Tokyo, Japan, and Seoul, South Korea, except for $SO_{2,}$ which increased in these two cities.

While several researchers investigated the impact of COVID-19 related activities on carbon monoxide (CO), only a few researchers studied the effect of COVID-19 related activities on CO_2 emissions (Andreoni, 2021; Chevallier et al., 2020; Han et al., 2021; Khan et al., 2021; Le Quéré et al., 2020; Liu et al., 2020). Khan et al. (2021) investigated the impact of COVID-19 lockdown measures on air quality, water quality, ozone, and carbon emissions, focusing on greatly affected select countries (e.g., the US, India, Italy, Spain, UK, Brazil, China, and few others). They found significant air quality improvement and reduction in carbon emissions from March 15 to April 15 of 2015–2019 and for the same duration in 2020. In a study on the impact of COVID-19 forced confinement on CO_2 emissions in 69 countries, 50 US states, and 30 Chinese provinces, which included 97% of global CO_2 emissions, Le Quéré et al. (2020) compared CO_2 emissions from January to April in 2019 with those in 2020 and found a 17% decrease in daily global CO_2 emissions. In-situ measurements were used in most investigations into the impact of COVID-19 related activities on CO_2 emissions, but Liu et al. (2020) used both in-situ measurements and satellite observations (e.g., Ozone Monitoring Instrument (OMI), Moderate Resolution Imaging Spectroradiometer (MODIS), and Greenhouse Gases Observing Satellite (GOSAT)) and quantified the impacts on the air mole fraction of CO_2, NO_2, and AOD. They primarily focused on the most impacted countries by June 2020 (e.g., China, U.S., India, Japan, Brazil, Russia, UK, Germany, France, Italy, and Spain), and found 3.7% (China) to 18.8% (Spain) of carbon reduction in 12 selected countries.

Several researchers have used satellite products to monitor CO_2 during the non-COVID/Pre-COVID periods, such as MODIS (Guo et al., 2012; Liu et al., 2020), GOSAT-1 and GOSAT-2 (Hamazaki et al., 2004; Liu et al., 2020) and Orbiting Carbon Observatory-2 (OCO-2) (Hakkarainen et al., 2019; Liu et al., 2020). However, Wang et al. (2021) reported that these data are applicable for a top-down approach to verify anthropogenic CO_2 emissions and have significant uncertainties for estimating natural CO_2 fluxes. On the other hand, Soil Moisture Active Passive (SMAP) carbon product has relatively low uncertainty and is still used for few global and regional studies. For example, Jones et al. (2017) validated SMAP carbon data using in-situ flux tower observations globally and found a relatively lower uncertainty (RMSE ≤ 1.6 g C m^{-2} d^{-1}). Ray et al. (2019) quantified spatial and temporal variabilities of CO_2 for selected terrestrial ecosystems across Texas during the 2015–2018 study period. They reported that SMAP carbon products could be used to study the terrestrial carbon cycle at regional to global scales.

Recent studies on the effects of COVID-19-related activities on air pollutants and GHG emissions used a few weeks to a few months of data from local to global scale. In general, the significance and consequences of lockdown measures are still poorly understood (Filonchyk et al., 2020). To the best of our knowledge, no studies investigated the impact of COVID-19 related activities on CO_2 emissions using satellite-based annual observations at a global scale due to the lack of data for the entire year before the end of 2020. The annual carbon emission data is essential to investigate the combined effects of COVID-19 related activities and climatic factors (e.g., temperature) on carbon emissions. While some studies found that the impact of climatic factors on air pollutants was secondary (Ghahremanloo et al., 2021; Pei et al., 2020), Broomandi et al. (2020) found a considerable impact of meteorological conditions on air pollutants in Iran.

This study investigated the effects of the COVID-19 pandemic on annual patterns or annual changes in carbon emissions from 2016 to 2020 globally, with a focus on several countries greatly affected by the COVD-19 pandemic. The main objectives of this study, therefore, were to: (i) investigate the effects of lockdown measures due to the COVID-19 pandemic on spatial distributions of annual CO_2 emissions; and (ii) quantify annual carbon emissions at global, continental, national, and city levels. We used SMAP level 4 (L4) daily carbon products to investigate the effects of the COVID-19 pandemic in 2020 and compared it with the emissions in prior years from 2016 to 2019. By focusing on change in global carbon emissions between pre-COVID-19 years (2016–2019) and COVID-19 year 2020, this study explored the possibilities of reducing carbon emissions by implementing preventative control measures to reduce overall GHG emissions, which support the global climate change initiative.

2. Materials and methods

2.1. Study area

The study included global Soil Moisture Active Passive (SMAP) satellite coverage between 180W to 180E and 85.044S to 85.044N (Fig. 1). First, we considered 184 countries to investigate this pandemic's impact on annual carbon emissions globally (Table S1). Then, we focused on 47 countries and their 105 major cities worldwide using data for the COVID-19 affected countries obtained from the Coronavirus Resource Center of Johns Hopkins University (accessed https://coronavirus.jhu.edu/), and the World Health Organization (WHO, 2021), https://covid19.who.int/table (accessed on January 1, 2021). We selected 45 countries greatly affected by the COVID-19 pandemic, with confirmed infections of more than 200,000 by December 31, 2020. In addition, we selected four, two, and one city of each country for confirmed infection rates ≥of one million, <one million ≥500,000, and <500,000 ≥200,000, respectively, by December 2020. Since our primary goal was to focus on most COVID-19 affected countries and their major cities worldwide, we also selected 105 major cities from 45 selected nations. In addition, we investigated one initially most affected countries by the COVID-19 and later well-recovered countries, China (two cities, Beijing and Wuhan) and other a little/not affected country, Vietnam (one city, Hanoi), to compare the impact of COVID-19 on carbon emissions between the most and least affected countries.

2.2. Data

2.2.1. Remotely sensed CO_2 data

This study used Soil Moisture Active Passive (SMAP) Level 4 carbon products (L4C) available at 9 km spatial resolution and daily temporal resolution (Entekhabi et al., 2014; Kimball et al., 2014). Although

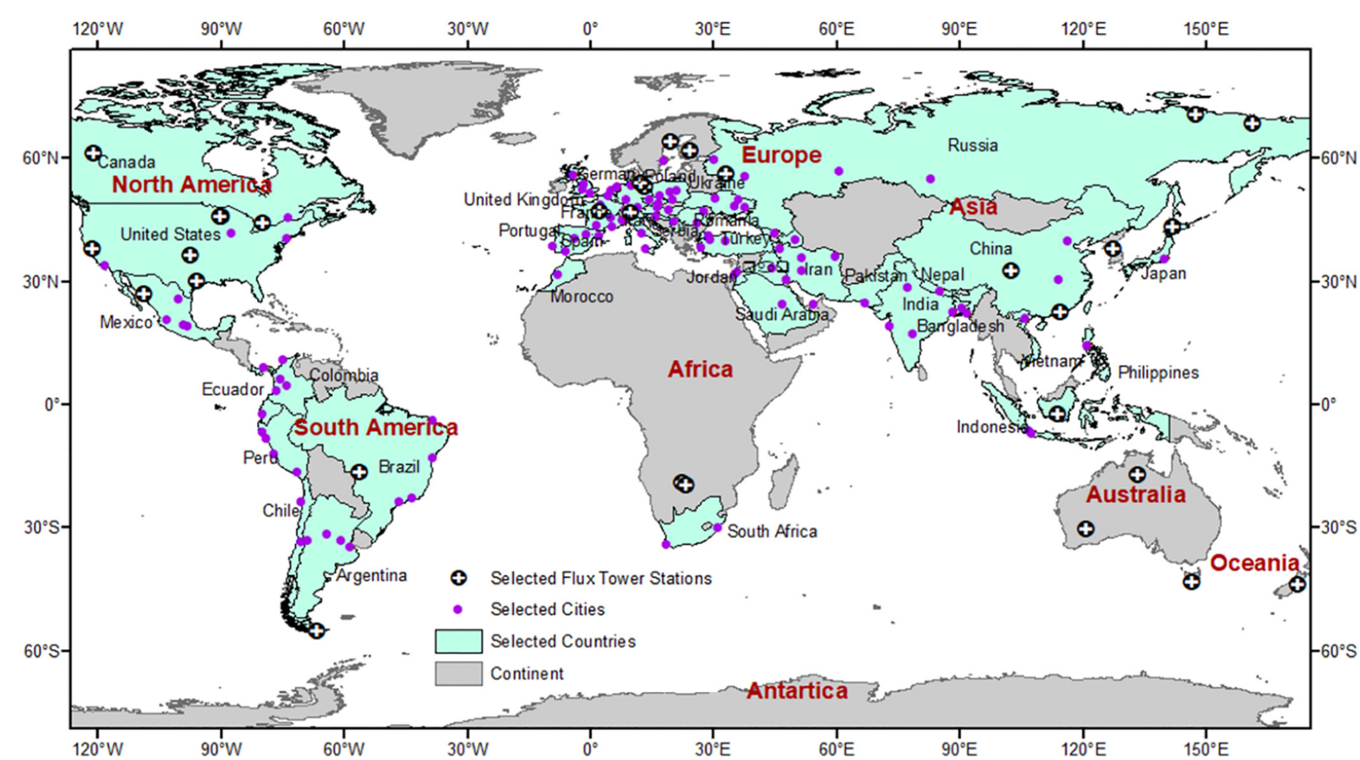

Fig. 1. Study area shows selected 47 countries, 34 eddy covariance (EC) flux towers, and 105 major cities worldwide.

SMAP estimates carbon at a relatively coarser resolution (9 km^2), it retains sub-grid scale heterogeneity information determined from the final scale (1 km^2). For example, SMAP estimates average carbon fluxes at a 9-km spatial scale as well as at a 1-km spatial scale if a 9-km^2 pixel has a 1-km^2 area covered with one of eight plant function types (e.g., a cereal crop, broadleaf crop, grass, shrub, etc.). SMAP L4C provides global gridded daily estimates of net ecosystem exchange (NEE) derived using a terrestrial carbon flux model integrated with SMAP L-band microwave observations, land cover, and vegetation inputs from the Moderate Resolution Imaging Spectroradiometer (MODIS), and Goddard Earth Observing System Model, version 5 (GOES-5) land model assimilation system. The SMAP, an environmental research satellite, was launched on January 31, 2015, by the National Aerospace Space Administration (NASA) to monitor soil moisture and freeze/thaw state at different spatial and temporal resolutions using radar and radiometric instruments (Jones et al., 2017; Ray et al., 2017; Ray et al., 2019).

SMAP L4C products were obtained from Earthdata web-based database developed by NASA called the Earth Observing System Data Information System (EOSDIS), https://earthdata.nasa.gov/. We used SMAP L4C daily CO_2 data from January 1, 2016, to December 31, 2020. We excluded CO_2 data for 2015 because it did not cover the entire year to obtain annual CO_2 measurements.

2.2.2. Eddy covariance CO_2 data

Although there are more than a hundred eddy covariance (EC) flux tower sites globally, only 34 sites were identified with CO_2 data during the study period (2015–2020). However, most of the stations lack in situ measurements after 2018. Only three stations had data available during the study period (2015–2020). Therefore, to be consistent, we compared in situ and SMAP data between 2015 and 2018. We downloaded half-hourly and daily CO_2 data, respectively, from AmeriFlux (https://ameriflux.lbl.gov) and FLUXNET (https://fluxnet.org). Specifically, we used FLUXNET-CH4 community products from the FLUXNET data portal (Knox et al., 2019).

2.2.3. Data on administrative boundaries

This study used global, continental, national, and city geospatial datasets. The global, continental and national geospatial data were obtained from the Environmental System Research Institute (ESRI, https://www.esri.com). The city geospatial data was obtained from the Made with Natural Earth (http://www.naturalearthdata.com/downloads/10m-cultural-vectors/, accessed on December 31, 2020).

2.3. Methods and analysis

This study considered different types of lockdown measures, including confinement defined by Le Quéré et al. (2020), which includes no restriction to mandatory national lockdown for a few weeks to several months globally in 2020. Le Quéré et al. (2020) described the confinement index on a scale of 0 to 3. Scale 0 indicates no restrictions; 1 indicates isolation of sick or symptomatic individuals; 2 indicates partial or full lockdown at selected regions, and 3 represents mandatory national lockdown in 2020. Since it is difficult to provide full details of confinement and the impact thereof on carbon emissions, this study evaluated the combined effects of lockdown measures on overall carbon emissions in the selected regions.

We used SMAP L4C product (Net Ecosystem CO_2 exchange (NEE)) and EC flux tower measurements to investigate the impact of COVID-19 on CO_2 emissions globally. We evaluated SMAP daily data using in-situ hourly and daily measurements obtained from EC flux tower sites. We downloaded half-hourly CO_2 data from AmeriFlux (Billesbach and Sullivan, 2019; Biraud et al., 2020; Kutzbach, 2018; Rey-Sanchez et al., 2021; Staebler, 2018; Vourlitis et al., 2018; Yepez, 2018) and converted half-hourly measurements to daily and monthly measurements. We also downloaded daily in-situ CO_2 data from FluxNet and OzFlux (Beringer, 2013; Laubach, 2019; Macfarlane, 2013; Phillips, 2015) and converted them to monthly measurements. Then, we analyzed and compared daily and monthly SMAP and EC flux tower measurements to derive correlation coefficients and the root mean square error (Table 1). A conceptual scheme of spatial and temporal analysis used to quantify annual CO_2 emissions (2015–2020) is presented in Fig. 2.

Table 1
Summary of statistics (correlation coefficient = R, and root mean square error = RMSE) for daily (D) and monthly (M) satellite and in-situ CO_2 at the 34 EC flux tower locations shown in Fig. 1.

S.N.	Stations	R-D	RMSE-D	R-M	RMSE-M	Source	Country
1	AR-TF2	0.27	1.01	0.44	17.23	AmeriFlux	Chile
2	BR-Npw	0.32	2.63	0.71	49.44	AmeriFlux	Brazil
3	CA-Cbo	0.49	3.47	0.84	48.82	AmeriFlux	Canada
4	MX-Aog	0.08	4.09	0.09	67.66	AmeriFlux	Mexico
5	US-A03	0.23	1.80	0.48	25.72	AmeriFlux	USA
6	US-ARM	0.32	2.41	0.23	53.71	AmeriFlux	USA
7	US-Bi1	0.23	4.65	0.36	98.11	AmeriFlux	USA
8	US-PVA	0.42	2.83	0.54	52.20	AmeriFlux	USA
9	US-A10	0.35	1.35	0.74	16.10	FluxNet	USA
10	US-EML	0.55	1.69	0.85	29.67	FluxNet	USA
11	US-Los	0.69	2.76	0.93	57.13	FluxNet	USA
12	US-Pfa	0.70	2.33	0.87	50.98	FluxNet	USA
13	CA-SCB	0.68	0.71	0.87	10.87	FluxNet	Canada
14	CH-DAV	0.48	3.58	0.76	85.43	FluxNet	Switzerland
15	CN-Hgu	0.25	3.88	0.61	37.87	FluxNet	China
16	HK-MPM	0.04	3.81	0.39	67.50	FluxNet	Hong Kong
17	ID-Pag	0.18	5.02	0.51	113.00	FluxNet	Indonesia
18	DE-Dgw	0.07	1.35	0.20	26.82	FluxNet	Germany
19	DE-Hte	0.47	2.74	0.88	42.49	FluxNet	Germany
20	FI-Si2	0.38	1.09	0.80	16.42	FluxNet	Finland
21	FI-Sii	0.55	1.03	0.74	19.81	FluxNet	Finland
22	FR-LGt	0.57	2.40	0.90	31.10	FluxNet	France
23	JP-BBY	0.70	2.41	0.84	50.82	FluxNet	Japan
24	KR-CRK	0.58	3.76	0.72	91.82	FluxNet	South Korea
25	RU-Che	0.77	0.82	0.89	13.87	FluxNet	Russia
26	RU-Cok	0.54	1.18	0.92	23.65	FluxNet	Russia
27	RU-Fy2	0.63	3.00	0.84	29.11	FluxNet	Russia
28	SE-Deg	0.62	0.89	0.70	19.65	FluxNet	Sweden
29	BW-Gum	0.19	3.28	0.79	64.30	FluxNet	Botswana
30	BW-Nxr	0.18	4.40	0.08	64.47	FluxNet	Botswana
31	ADdry	0.36	2.15	0.64	34.31	OzFlux	New Zealand
32	GWW	0.36	0.68	0.19	12.17	OzFlux	Australia
33	SturtPlains	0.56	0.99	0.80	19.49	OzFlux	Australia
34	Warra	0.23	2.80	0.21	47.20	OzFlux	Australia
	Average	0.41	2.44	0.63	43.79		

Annual spatial maps of SMAP CO_2 were developed using daily estimates during the study period (2016–2020). Daily SMAP CO_2 estimates ($g\ C\ m^{-2}\ d^{-1}$) were used to estimate annual CO_2 ($g\ C\ m^{-2}\ yr^{-1}$) each year. Since SMAP L4C data were available only for nine months in 2015, this year was excluded from the analysis. ArcGIS (Spatial Analyst-Zonal Statistics tool) was used to summarize the average annual CO_2 at the city, national, and continental scales. Also, the spatial changes in yearly CO_2 emissions between 2016–2019 and 2019–2020 were calculated.

3. Results

3.1. Evaluation of satellite CO_2 using EC flux tower measurements

This study evaluated SMAP LC4 products using eddy covariance (EC) flux tower observations worldwide. It is important to evaluate satellite observations using in-situ and/or modeled measurements. However, it is always a challenge to evaluate coarse resolution satellite data using point scale in-situ measurements. The SMAP satellite footprint is 9 km × 9 km. The EC flux tower measurements, which are point scale measurements, have a few square meters to a few hundred square meters of footprint.

This study compared daily and monthly in-situ and SMAP CO_2 (Table 1 and Fig. S1). Since SMAP measurements were available from

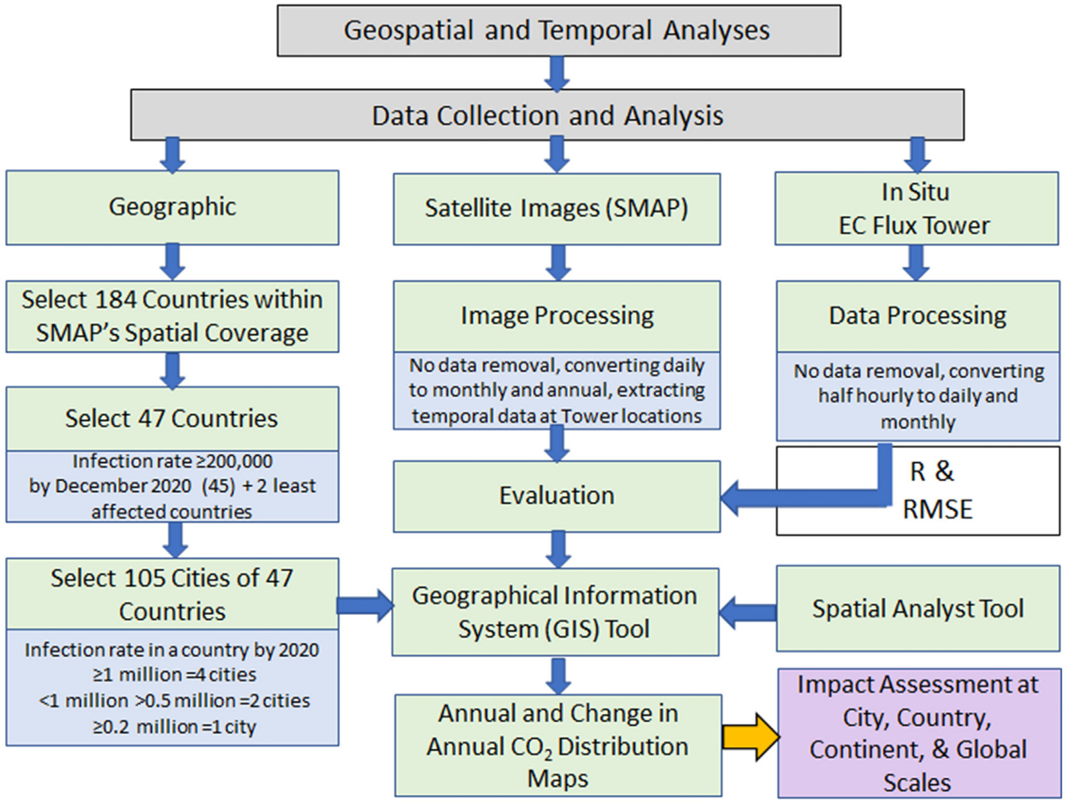

Fig. 2. A conceptual scheme for geospatial and temporal analyses used for quantifying CO_2 emissions globally.

April 2015, and AmeriFlux and FluxNet data were available until 2018, SMAP data was evaluated using four years of data (2015–2018). Despite considerable scale differences between these two measurements (SMAP and EC Flux Tower), the agreement between in-situ observations and SMAP CO_2 measurements was reasonable.

For a quantitative assessment, the performance of SMAP CO_2 was evaluated using the correlation coefficient (R), and the root mean square error (RMSE). Among 34 EC Flux Tower stations, the majority of stations showed good to very good agreements, for monthly (M) and daily (D) measurements ((R-M = 0.54 to 0.93 (23 locations) and R-D = 0.54 to 0.77 (13 locations)). Only nine locations had R-values less than 0.25 for daily comparison, and six locations had R-values less than 0.25 for monthly comparison. Daily RMSE ranged from 0.68 to 5.02 g C m^{-2} d^{-1}, and monthly RMSE ranged from 10.87 to 113.00 g C m^{-2} mo^{-1}. Most of the stations that showed poor correlations with the SMAP carbon measurements are located near water bodies or barren lands. On average, among 34 locations, the observed R and RSME were 0.41, 2.44 g C m^{-2} d^{-1}, and 0.63 and 43.79 g C m^{-2} mo^{-1} for daily and monthly measurements, respectively (Table 1). Please refer to (Jones et al., 2017) for detailed evaluations of SMAP CO_2 products.

Based on these correlation coefficients, considering the scale differences, the agreements can be considered reasonable between in-situ measurements and SMAP estimates, considering the scale difference between the two data sets. However, some locations had higher uncertainty than the estimated uncertainty threshold (1.6 g C m^{-2} d^{-1}), mainly due to land-use heterogeneity in particular areas. Also, two EC flux tower stations located close to the ocean had poor performance (MX-Aog, and DE-Dgw). The total daily uncertainty (RMSE) was expected as 1.6 g C m^{-2} per day (Kimball et al., 2014). Jones et al. (2017) validated SMAP NEE using in-situ EC flux tower observations from 26 validation sites worldwide. They found the NEE performance within the targeted accuracy threshold (RMSE ≤ 1.6 g C m^{-2} d^{-1}) for NEE over 66% of the global domain.

3.2. Annual changes in CO_2 emissions at global and continental levels

Changes/differences in the spatial distribution of annual CO_2 emissions between 2019 and 2020 and between 2016 and 2019 were compared, as shown in Fig. 3a and b. The differences were grouped into nine classes to understand the spatial distribution ranges of CO_2 emissions globally. Most of the northern hemisphere (continents of North America, Europe, and Asia) had higher carbon emissions in 2019 than in 2016 (1–100 g C m^{-2} yr^{-1}). By contrast, most of the southern hemisphere (continents of South America, Africa, except Australia) had higher carbon uptakes (<0 to −299 g C m^{-2} yr^{-1}). However, the continent of Australia had higher carbon emissions in the range of 1 to 300 g C m^{-2} yr^{-1} in 2019 than in 2016. Most of the northern hemisphere (continents of North America, Europe, and Asia) had higher carbon uptakes in 2020 than in 2019 (<0 to −99 g C m^{-2} yr^{-1}), whereas the north-western part of the continents of South America and Africa had higher carbon emissions (1–300 g C m^{-2} yr^{-1}). Also, most of the Australian continent had slightly lower carbon emissions (1 to 100 g C m^{-2} yr^{-1}) in 2020 than in 2019.

Fig. 4a compares the spatial coverage (%) of specified annual CO_2 ranges during the study period (2016–2020), and Fig. 4b compares the change in the spatial coverage of specified annual CO_2 ranges between the two selected durations: 2016–2019 and 2019–2020. The spatial coverage of annual CO_2 distribution for each year is presented in supplementary Fig. S2. Although we classified the spatial distributions of CO_2 into nine classes, only four out of nine (−299 to −100; −99–0; 1–100; 101–300 g C m^{-2} yr^{-1}) classes had significant coverages. For example, during the study period, about 99% of the area had CO_2 emissions or uptakes between −299 to 300 g C m^{-2} yr^{-1}. 8 to 11% and 38 to 49% of the global area had carbon uptakes between −299 and −100, and −99 and 0 g C m^{-2} yr^{-1}, respectively. Here, 8 to 11% indicates the minimum % of the global area (e.g., 8% in 2018), and the maximum % of the global area (e.g., 11% in 2016) had carbon

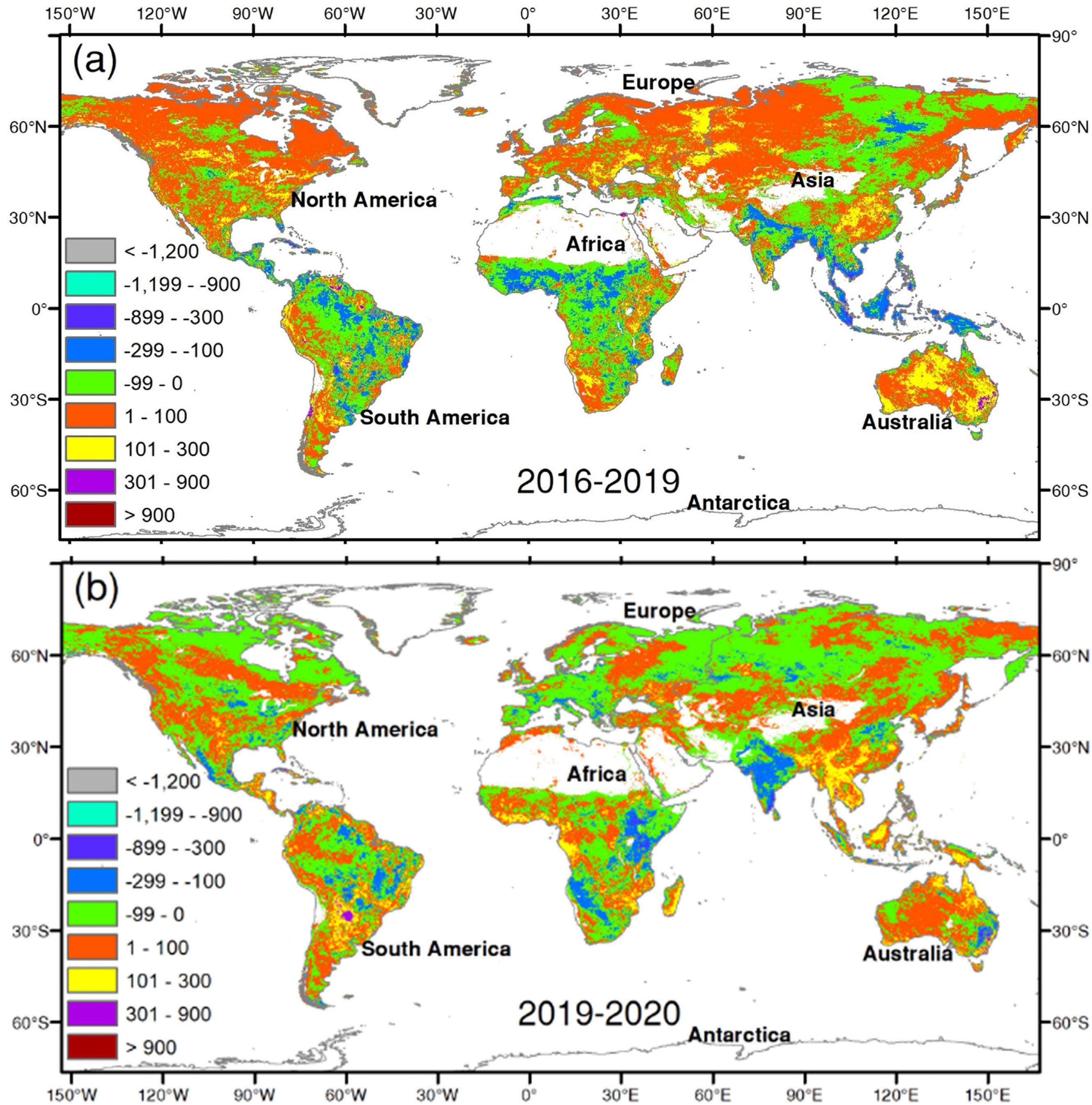

Fig. 3. Change in the spatial distribution of annual CO_2 emissions (g C m^{-2} yr^{-1}) between (a) 2016 and 2019 and (b) 2019 and 2020 globally. The negative value indicates carbon uptakes, whereas the positive value indicates carbon emissions.

uptakes between −299 to 300 g C m^{-2} yr^{-1} during the study period (2016–2020). On the other hand, 5 to 9% and 34 to 51% of the global area had carbon emissions between 1 and 100, and 100 and 300 g C m^{-2} yr^{-1}, respectively. These classifications help understand high and low spatial distributions of CO_2 emissions and uptakes globally during the study period. The positive and negative values indicate carbon emissions and uptakes, respectively.

In 2016, 49% of the global area had carbon uptakes from 0 to −99 g C m^{-2} yr^{-1}, which decreased to 38% in 2019, and increased to 41% in 2020. On the other hand, 33% of the global area had carbon emissions from 1 to 100 g C m^{-2} yr^{-1} in 2016, which gradually increased to 45% in 2019, then decreased to 40% in 2020. Even though spatial coverages of carbon emissions and uptakes in the range of 101 to 301 and −299 to −100 g C m^{-2} yr^{-1} were small (≤10%), respectively, 2020 had relatively higher carbon uptakes than had other years.

As shown in Fig. 4b, between 2016 and 2019, 51% of the global area had carbon emissions from 1 to 100 g C m^{-2} yr^{-1}, whereas between 2019 and 2020, only 40% of the global area had carbon emissions from 1 to 100 g C m^{-2} yr^{-1}. On the other hand, between 2016 and 2019, 31% of the global area had carbon uptakes from 0 to −99 g C m^{-2} yr^{-1}, whereas between 2019 and 2020, they were 48% (Fig. 4b). While 5.6% of the global area had carbon emissions from 100 to 300 g C m^{-2} yr^{-1} between 2019 and 2020, the difference between 2016 and 2019 was 8%. On the other hand, 6.4% global area had carbon uptakes from −299 to −100 g C m^{-2} yr^{-1} between 2019 and 2020, and the difference between 2016 and 2019 was 8.4%.

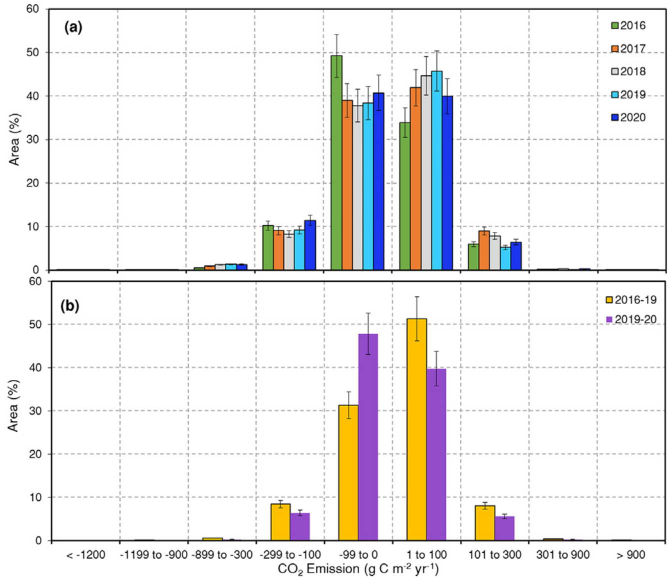

Fig. 4. Spatial coverage of specified (particular) annual CO_2 distribution ranges (a) 2016 to 2020, and (b) difference between 2016 and 2019, and 2019 and 2020 globally. The coverage areas for respective years, including the difference between 2016 and 2019, and between 2019 and 2020, are in percentage. The straight line in each bar indicates standard error (SE). The negative value indicates carbon uptakes, whereas the positive value indicates carbon emissions.

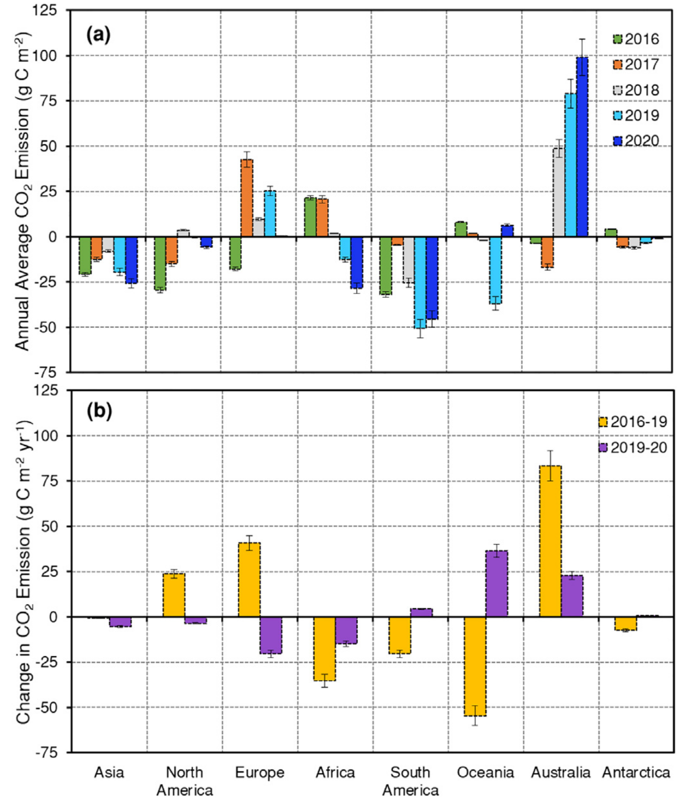

Fig. 5. (a) Annual average CO_2 emissions, and (b) change in annual CO_2 emissions between 2016 and 2019, and 2019 and 2020 at the continental level. The differences in annual carbon emissions were calculated by subtracting the annual emissions of 2019 from 2020. The straight line in each bar indicates a standard error (SE).

Overall, the spatial reduction in carbon emissions and increase in carbon uptakes were observed in 2020 compared to other years, which could be attributed to the reduction of traffic and industrial activities or the impact of lockdown measures globally.

As shown in Fig. 5a, annual carbon emissions and uptakes varied in different continents before and during the COVID-19 pandemic. Results showed while Asia and South America had carbon uptakes from 2016 to 2020, North America had carbon uptakes from 2016 to 2017 and 2019 to 2020, but had carbon emissions in 2018. By comparison, Europe had carbon emissions each year, except in 2016, which had carbon uptakes. Interestingly, Australia, which has a comparatively lower impact of COVID-19, had carbon emissions each year, except in 2016 and 2017.

Fig. 5b depicts the difference in annual carbon emissions between 2016 and 2019, and between 2019 and 2020 in each continent. Results showed a reduction in annual carbon emissions in Asia, North America, and Europe in 2020 compared to 2019 and a rise in all other continents. In Asia, North America, and Europe, a notable reduction in carbon emission was observed in 2020 compared to 2019. By contrast, while a notable increase in carbon emissions was observed in Oceania and Australia, a slightly higher carbon emission was observed in Africa, South America, and Antarctica. Regarding the difference in annual carbon emissions between 2016 and 2019, results showed a significant increase in annual carbon emissions in North America, Europe, and Australia, whereas a significant decrease in Africa, South America, Oceania, and the Antarctica. However, in Asia, a slight decrease in carbon emission was observed in 2019 compared to 2016. An increasing annual carbon emission trend was observed between 2016 and 2019 in the continents of North America, Europe, and Australia, which include most developed countries. On the other hand, a decreasing trend in annual carbon emissions was observed in the continents of South Africa, Asia, and South America, which include developing and least-developed countries, as well as Antarctica and Oceania.

3.3. Changes in annual CO_2 emissions at country and city levels

Fig. 6 shows the differences in annual carbon emissions (g C m^{-2} yr^{-1} and Mt C yr^{-1}) between 2016 and 2019 and between 2019 and 2020 in the selected 47 countries ranked in descending order. Since regular human activities entirely impacted carbon emissions during non-COVID periods (2016–2019), only a few countries showed decreasing annual CO_2 emission trends (Fig. 6a). For example, only 13 out of 47 countries (Philippines, Indonesia, Bangladesh, Vietnam, Panama, India, Colombia, Pakistan, Brazil, Morocco, Iraq, Nepal, and Iran) showed lower annual carbon emissions (7 to 197 g C m^{-2} or, 4 to 405 Mt C) in 2019 than in 2016. Thirty-four select countries had more carbon emissions in 2019 than in 2016. Interestingly, those 34 countries with more carbon emissions in 2019 include both developed and developing countries.

As shown in Fig. 6b, some countries showed a significant response to lockdown measures imposed in 2020, compared to no measures imposed in 2019. For example, India had 103 g C m^{-2} or 325 Mt less carbon emission in 2020 than in 2019. Similarly, Italy, Spain, France, Germany, Brazil, Russia, and the USA also had significantly lower annual carbon emissions (6 to 69 g C m^{-2} or 13 to 273 Mt C) in 2020 than in 2019. On the other hand, Vietnam, Bangladesh, Ecuador, Azerbaijan, Argentina, Japan, and Iraq showed more annual carbon emissions (36 to 122 g C m^{-2} or 10 to 148 Mt C) in 2020 than in 2019, because of little or no strict restrictions, or lockdown measures for a smaller duration in 2020.

Fig. 7 shows the differences in annual carbon emissions (g C m^{-2} yr^{-1}) between 2016 and 2019, and 2019 and 2020 in the 47 selected countries ranked in descending order and their 105 major cities. Twenty-five countries and their 65 major cities showed a decrease in annual carbon emissions in 2020 than in 2019 (Fig. 7a). By contrast, 22 countries and their 40 major cities showed an increase in annual carbon emission in 2020 than in 2019 (Fig. 7b).

As shown in Fig. 7a, 25 countries (e.g., India, Hungary, Italy, Serbia, Croatia, Pakistan, Poland, Chez Republic, Austria, Switzerland, Spain, France, Romania, Germany, Mexico, South Africa, and few others) had lower carbon emissions in 2020. Not all of the selected major cities of

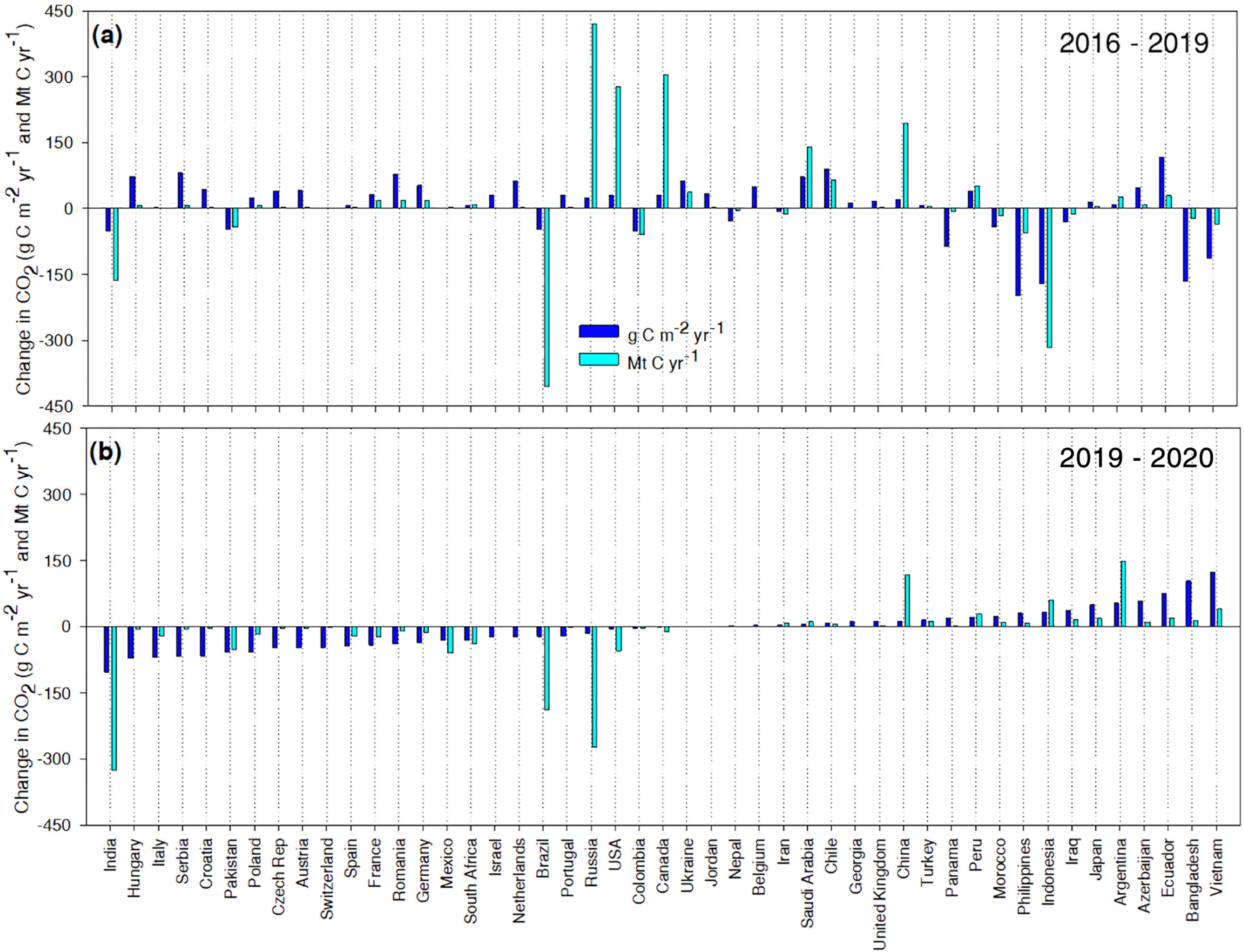

Fig. 6. Change in CO_2 emissions (g C m^{-2} yr^{-1} and Mt C yr^{-1}) between (a) 2016–2019 and between (b) 2019–2020 in the selected 47 countries. The differences in annual CO_2 emissions between 2019 and 2020 were ranked in descending order (Higher −ve value indicates the lower carbon emissions in 2020 than in 2019, and so on). The differences in annual carbon emissions were calculated by subtracting the annual emissions of 2019 from 2020.

those 25 countries showed lower emissions in 2020 than in 2019. Since reduced carbon emissions in 2020 were attributed to types, levels, and lengths of confinement or lockdown measures, each city showed a different response to carbon emissions with respect to the lockdown measures. For example, four major cities in India had significantly different annual carbon emission rates. The difference in annual CO_2 emissions between 2019 and 2020 was estimated from −8.6 to −177 g C m^{-2} yr^{-1} in Delhi, Hyderabad, Kolkata, and Mumbai. By contrast, annual carbon emissions increased in Mumbai (95.7 g C m^{-2} yr^{-1}) and decreased in three major cities in India (−20 to −170 g C m^{-2} yr^{-1}) between 2016 and 2019. These increasing and decreasing annual carbon emissions trends were observed in several other cities, even though the country had lower annual carbon emissions in 2020 than in 2019 at the national level (Fig. 7a).

As shown in Fig. 7b, 22 countries (Jordan, Nepal, Belgium, Iran, Saudi Arabia, Chile, Georgia, UK, China, Turkey, Peru, Morocco, Philippines, Indonesia, Iraq, Japan, Argentina, Azerbaijan, Ecuador, Bangladesh, and Vietnam) had higher carbon emissions (0.5 to 122 g C m^{-2} yr^{-1}) in 2020 than in 2019. However, all of the selected major cities of those 22 countries did not show higher carbon emissions in 2020 than in 2019. Instead, some cities had higher annual carbon emissions, while others had lower carbon emissions. For example, Kathmandu (Nepal), Tbilisi (Georgia), Tokyo (Japan), Baku (Azerbaijan), Guayaquil (Ecuador), and Hanoi (Vietnam) had higher carbon emissions in 2020 than in 2019, which aligns with the average annual emissions at the national level. However, Irbid (Jordan), Antwerp (Belgium), Manila (Philippines), and Santiago (Chile) had lower carbon emissions in 2020 than in 2019, but they were not in alignment with the average annual emissions at the national level. These variations might be attributed to the heterogeneous effects of COVID-19 national lockdowns compared to the few large cities. On the other hand, some countries, such as China, had higher annual carbon emissions at a national level, but two selected cities (Beijing and Wuhan) had lower carbon emissions in 2020 than in 2019. These differences could be attributed to the lockdown measures imposed by the selected cities but not at the national level. Several countries (e.g., Argentina, Peru, Turkey, UK, and Iran) had higher carbon emissions in 2020 than in 2019 at the national level, yet had lower carbon emissions in 2020 at the city level, which could be attributed to the effects of lockdown measures for particular cities (Table S1).

By comparison, most cities and nations showed higher carbon emissions in 2019 than in 2016 and lower carbon emissions in 2020 than in 2019 (Fig. 7a and b). Since the impact of lockdown measures on carbon emissions was not consistent for all cities within the country and among countries, the varying effects were observed in differences of annual CO_2 emissions between 2019 and 2020 because of significantly different human activities attributed to carbon emissions between cities within the country and among countries. The same reasons for varying effects of human activities could be for annual carbon emission changes between 2016 and 2019 under normal conditions.

Annual carbon emission in Mt C yr^{-1} was calculated using estimated annual carbon emissions in g C m^{-2} yr^{-1} for each country (Table S1). Maximum (MAX) and minimum (MIN) annual carbon emissions and their differences between 2016 and 2019, and between 2019 and 2020 for each country are presented in Table 2. The standard deviations (Std Dev) of annual carbon emissions among 184 countries are also presented in Table 2.

Australia had consistently maximum carbon emissions from 2018 to 2020 (376 to 784 Mt C yr^{-1}), and Brazil had carbon uptakes of 590 and 779 Mt C yr^{-1}, respectively, in 2019 and 2020 among 184 nations (Table 2). India had 325 Mt lower carbon emissions in 2020 than in 2019, and Brazil had 779 Mt lower carbon emissions in 2019 than in 2016. In 2016, the US had carbon uptakes of 463 Mt, and Algeria had carbon emissions of 229 Mt. On the other hand, in 2017, Egypt had annual carbon uptakes of 424 Mt, and Russia had 264 Mt. The higher or lower annual carbon emissions for each country relied on human activities that directly impacted carbon emissions during the non-COVID period. However, the sudden reduction in carbon in 2020 was attributed to lockdown measures imposed on several countries. Globally, results showed an increasing annual carbon emission trend from 2016 to 2019 and a significant decrease in 2020, attributed to the lockdown measures worldwide.

4. Discussion

Recently, researchers reported that lockdown measures imposed to reduce the impact of COVID-19 pandemic had shown a considerable reduction in air pollution and greenhouse gas emissions worldwide (Balasubramaniam et al., 2020; Baldasano, 2020; Chekir and Ben Salem, 2021; Chen et al., 2020; Filippini et al., 2020; Griffin et al., 2020; Gulabchandani and Sethi, 2020; Gupta et al., 2020; Ju et al., 2021; Kumari and Toshniwal, 2020; Liu et al., 2020; Mahato and Ghosh, 2020; Mostafa et al., 2021; Singh et al., 2020). Moreover, they found an improvement in the ozone layer and an overall positive impact on several other aspects, including air and water qualities. Even though the infection rate of COVID-19 increased in several countries, governments could not continue lockdown measures for prolonged periods in order to reduce the adverse impact on the economy. Several countries either entirely or partially lifted strict lockdown measures, while the COVID-19 infection was still rising in 2020.

The effects of lockdown measures on carbon emissions were not consistent among cities within the country or among countries because levels, types, and lengths of lockdown measures imposed in the cities within the same country and among countries were different. Some countries imposed lockdown measures for a few weeks or a few months in few cities or a few states, whereas others imposed lockdown measures for several months and several cities/states in a nation. Consequently, even though lockdown measures helped reduce carbon emissions, the spatial distributions of annual carbon emissions varied globally.

Results showed lower carbon emissions in highly impacted continents and higher carbon emissions in slightly impacted continents. The rate of infections appeared directly proportional to lockdown measures' strictness and inversely proportional to carbon emissions. The countries in North America, Europe, and Asia, which were greatly affected by the COVID-19 pandemic, implemented strict lockdown measures to stop the spread of the disease, which caused significant reductions in annual carbon emissions in 2020. On the other hand, countries in the north-western part of the continents of South America, Africa, and Australia were only slightly affected by the COVID-19 pandemic and did not implement strict lockdown measures to stop the spread of the disease. They had higher annual carbon emissions in 2020. These results support the findings of earlier short duration (monthly to semi-annual) studies, such as by Han et al. (2021), that lockdown measures significantly reduced carbon emissions.

Overall, the spatial reduction in carbon emissions and increase in carbon uptakes in 2020 compared to other years were observed. This could be attributed to the reduction in traffic (ground, water, and air), agricultural and industrial activities globally.

Le Quéré et al. (2020) and Liu et al. (2020) identified five different sectors that could impact carbon emissions during lockdown measures, power generation and industry, cement production, ground transportation, aviation, and shipping emissions, and commercial and residential buildings. Several countries and several cities within an impacted country may have had intensive curtails in the operation of all five sectors or a few sectors during the complete or partial lockdowns. Since all five sectors had different impacts on carbon emissions, the effects of lockdown measures were different among cities within a country or among nations globally. India had the highest carbon emission reduction (−103 g C m^{-2} or –325 Mt) in 2020 than in 2019 among 184 selected nations because they imposed strict lockdown measures nationwide for extended periods in 2020, which curtailed operations

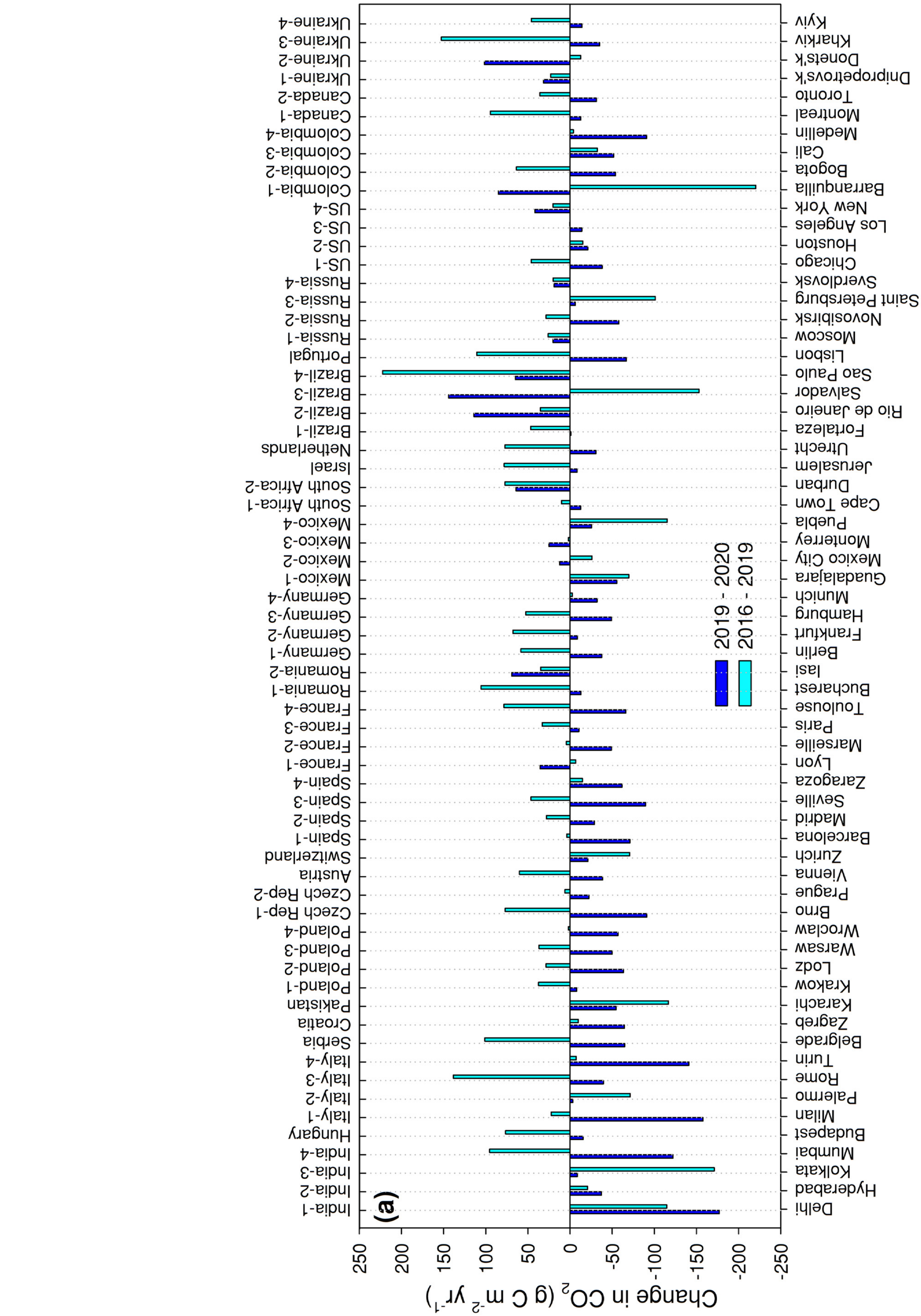

Fig. 7. Change in CO_2 emissions (g C m^{-2} yr^{-1}) between (a) 2016 and 2019, and (b) 2019 and 2020 at the 105 major cities of selected 47 countries. Fig. 7a includes 25 countries and their 65 major cities, which showed a decrease in annual carbon emission in 2020, whereas Fig. 7b includes 22 countries and their 40 cities that had an increase in annual carbon emissions in 2020. The differences in annual carbon emissions were calculated by subtracting the annual emissions of 2019 from 2020.

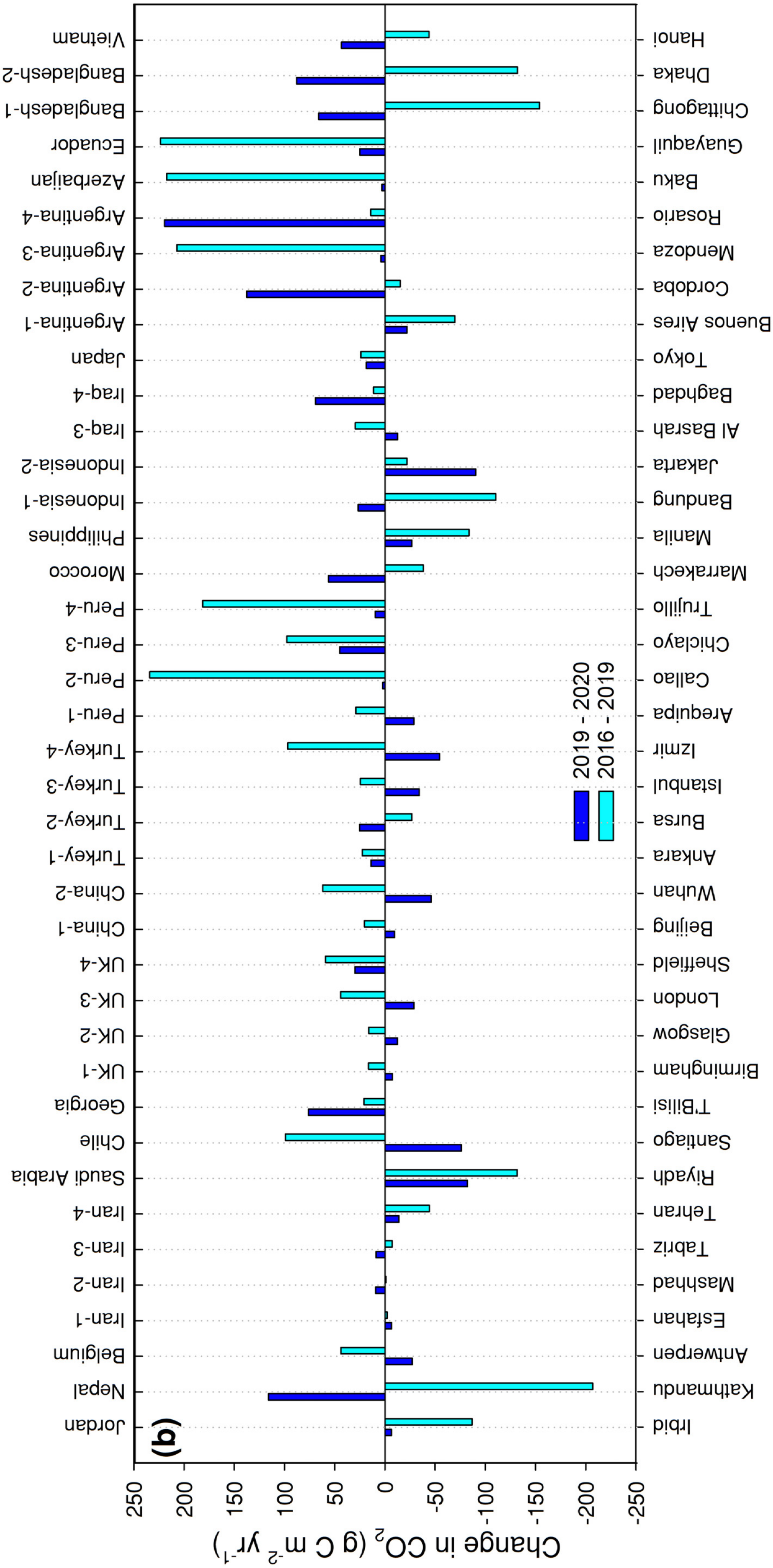

Fig. 7 (*continued*).

Table 2
Maximum, minimum, and standard deviations of annual carbon emissions among 184 countries in Mt C yr^{-1}. The differences between annual carbon emissions between 2016 and 2019 and 2019 and 2020. The country's name with maximum and minimum annual emissions for the respective year is included in the parenthesis.

	2016	2017	2018	2019	2020	2016–19	2019–20
Max	229 (Algeria)	264 (Russia)	376 (Australia)	609 (Australia)	784 (Australia)	637 (Australia)	176 (Australia)
Min	−463 (USA)	−422 (Egypt)	−424 (Egypt)	−590 (Brazil)	−779 (Brazil)	−405 (Brazil)	−325 (India)
Std Dev	65	58	64	82	103	86	45
Global	8	1635	1559	236	−202	224	−438

in almost all of the five sectors previously discussed. Similarly, Italy, Spain, France, Germany, Brazil, Russia, and the US also showed significantly lower annual carbon emissions in 2020 because these countries also curtailed operations of all five sectors for extended periods in 2020. On the other hand, a few countries, such as Vietnam, Bangladesh, Japan, Iraq, and a few others, that had not imposed strict lockdown measures or significantly curtailed the operations of the sectors mentioned above, showed an increase in carbon emissions in 2020.

Delhi and Mumbai, the two largest cities in India, had higher carbon reductions at the city level, −177 and −122 g C m^{-2}, respectively, in 2020 than in 2019 among the 105 selected cities worldwide. Both Indian cities were impacted mostly by the COVID-19 pandemic and had complete lockdowns for several months. Similarly, Milan and Turin, located in northern Italy, severely affected by COVID-19, imposed strict lockdown measures, had higher carbon reductions (−157.7 and −140.9 g C m^{-2}) than had Rome and Palermo (−39.5 and −3.3 g C m^{-2}).

Ongoing economic and environmental activities also impacted variations in annual carbon emissions among cities and nations during the lockdowns. Like different air pollutants have different emission sources, characteristics, and spreading behaviors (Liu et al., 2021), CO_2 also has different emission sources. Therefore, it depends on how lockdown measures were implemented to control the spread of COVID-19 and how they impacted carbon emission sources. For example, lockdown measures created opportunities to work remotely to reduce the activities that directly reduce carbon emissions. These activities align with the unprecedented declines in air and ground travels and industrial activities, profoundly impacting carbon emissions (Hale and Leduce, 2020). Results support the idea that carbon emissions were substantially reduced in cities where transports and industries were major sources. However, carbon emission reduction during COVID-19 lockdowns may not clearly favor areas with a more complex mix of sources, such as transport and industrial emissions, smaller than other sources.

Indeed, a significant impact of lockdown measures on carbon emissions was observed across the globe in 2020. However, we cannot underestimate the impact of climatic factors, such as a change in temperature on carbon emissions in 2020 compared to 2019. There are several factors, including the impact of climate change, which did not let the seasonal temperature be consistent between the years. The non-COVID year's winter/summer season in the northern hemisphere might differ from the COVID-19 year's winter/summer season in the southern hemisphere. For example, Spring 2020 was colder than Spring 2019 in Ontario, Canada (Griffin et al., 2020), March 2019 was warmer than March 2018/2020 in Spain (Baldasano, 2020). Liu et al. (2020) found the first months of 2020 were exceptionally warmer across much of the northern hemisphere than in the same period in 2019, which caused lower CO_2 emissions in 2020 than in 2019 when no external forces were present.

Varying temperature, precipitation, and other climatic and social factors could also have impacted carbon emissions in 2020 because each country had faced the COVID-19 pandemic simultaneously (e.g., within few weeks to few months apart), despite the difference in geographical location. In addition, different seasons across the globe also had a significant impact on carbon emissions because there were more carbon emissions in winter than in summer. Similar lockdown measures during the colder and warmer seasons could have a different effect on carbon emissions.

Since most countries imposed strict lockdown measures from March to August in 2020, except in China, seasons (e.g., winter versus summer) also played a significant role in increasing or decreasing carbon emissions globally. For example, Han et al. (2021) used gross domestic product (GDP) to estimate carbon emissions at the province and national levels. They found 257.7 Mt lower carbon emissions in the first three months of 2020 than in the first three months of 2019 in China due to reduced fossil-related and cement-induced carbon dioxide (CO_2) emissions in China. However, we found 118 Mt more carbon emissions in 2020 than in 2019, despite reductions in Beijing and Wuhan's annual carbon emissions. In these states, while the lockdown reduced the CO_2 emissions in the first three months, the reopening could have brought emissions back on track compared to previous years, which aligned with Liu et al.'s (2021) findings. The carbon emissions, rebounding to pre-lockdown levels, once the strict measures were lifted, could be the reason for a smaller annual carbon reduction or even an increase in 2020 than initially estimated in the first half of 2020 by several researchers (Han et al., 2021; Le Quéré et al., 2020; Liu et al., 2020).

Le Quéré et al. (2020) compared four months (January to April) of carbon emissions between 2020 and 2019 and found significant carbon reductions globally (−1048 Mt) and in select countries (China −242 Mt; USA −207 Mt, Europe −123 Mt, and India −98 Mt). Liu et al. (2020) compared six months (January to June) of carbon emission between 2020 and 2019 and found significant carbon reductions globally (−1551 Mt) and in select countries (China −187.2 Mt; USA −338.3 Mt; Europe and UK −205.7 Mt; India −205.2 Mt; Japan −43.1 Mt; Russia −40.5 Mt; and Brazil −25.2 Mt). Except for China, in most countries, lockdown measures were in effect until June 2020. Therefore, these two studies showed reasonable decreases in carbon emissions globally and in the selected countries. On the other hand, China lifted lockdown measures in early April 2020, which caused an increase in carbon emissions after April 2020. Liu et al. (2020) found an increase in carbon emissions in China three months after the lockdown measures ended. In China, annual carbon emissions increased to −187.2 Mt (−242 Mt between January and April to −187.2 Mt between January and June). Nevertheless, quarterly and half-yearly studies, which showed promising reductions in carbon emissions, suggested considering these findings as a temporary change that depends on the duration, degree, and extent of lockdown measures applied to the rest of the year.

We found significantly different annual carbon emissions in 2020 compared to 2019 in several countries. We found 118, 18.4, 2.7 Mt more carbon emissions in 2020 than in 2019, respectively, in China, Japan, and the UK. However, India, Russia, and Brazil had, respectively, 324.8, 273, and 188.5 Mt lower carbon emissions in 2020 than in 2019.

Overall, the total carbon emissions in the 184 selected countries were reduced by 438 Mt in 2020 compared to 2019. This reduction could be attributed to the continued lockdown measures and the impact of climatic factors (e.g., decrease in temperature in 2020 over 2019) in several countries. We found a significant reduction in annual carbon emissions in 2020 compared to 2019 in several cities and countries which imposed strict lockdown measures for extended periods in 2020. On the other hand, we found an increase in annual carbon emissions in 2020 compared to 2019 (a similar increasing trend in post-

COVID years 2016 to 2019) in several cities and countries which had either no significant impact of the COVID-19 pandemic or lockdown measures were not adopted for extended periods in 2020.

The COVID-19 pandemic has brought both challenges and opportunities globally. While the significant negative impact of COVID-19 on human health, societies, and the economy are challenges, reduction in environmental pollutions and supports in climate change initiatives are the opportunities. Assessing the impact of the COVID-19 pandemic on CO_2 emissions, a time frame on which analysis is based and control measures are implemented plays a critical role (Hoang et al., 2021b). The emissions of CO_2 and other air pollutants are directly linked to anthropogenic activities (Nguyen et al., 2021). It is not possible imposing partial or complete lockdown measures for an extended period. Therefore, we have to formulate or develop policies that have minimum or no negative impact on the economy but are still enough to reduce anthropogenic activities that caused significant GHG emissions. For example, during the pandemic, we learned several human activities could be done remotely, which helps reduce burning fossil fuels, one of the number one causes of GHG emissions. Therefore, taking advantage of lessons learned during the COVID-19 pandemic, governments should develop and implement the most robust measures to curb global carbon emissions and mitigate the irreversible consequences of climate change to ensure a sustainable path for a post-pandemic world.

5. Conclusion

While continuous in-situ CO_2 emission measurements are scarce globally, the remotely sensed carbon products, such as SMAP LC4 products, provide opportunities to monitor and quantify the change in carbon emissions from the local to the global scale. This study used SMAP L4C products to quantify the difference in annual CO_2 emissions in cities, nations, and continents from 2016 to 2020. It aligns with several recent studies on how lockdown measures significantly impacted carbon emissions in the short run. Although the reduction in carbon emissions was temporary, it did show that if appropriate regulations are adopted at the city, nation, continent, and global levels, we can reduce carbon emissions in the long run.

This study revealed several major cities and countries with intensive carbon emissions-related operations and imposed lockdown measures for extended periods significantly reduced carbon emissions in 2020. By contrast, several major cities and countries either slightly impacted by COVID-19 or not adopting strict lockdown measures had a slight or no impact on carbon emissions in 2020 compared to 2019.

In conclusion, we agree with Hale and Leduce (Hale and Leduce, 2020) that without substantial and sustained changes in human activities that cause an increase in carbon emissions, it may not be possible to reduce carbon emissions significantly in the long run. However, the lesson learned from this COVID-19 pandemic can help policymakers and communities adopt appropriate measures to curtail carbon emissions in the long-run. Moreover, opportunities exist to implement strategies to curtail carbon emissions using the lessons learned during the COVID-19 pandemic.

This study has some limitations. The lengths, degrees, and types of lockdown measures imposed in the selected major cities and nations were not investigated. Some countries or regions were excluded from the study due to the lack of satellite/SMAP data (Fig. 1). Further, the SMAP footprint is 9 km × 9 km, which excludes smaller countries or territories from the study, caused the total number of investigated countries to be 184. Also, SMAP L4C excludes high-density urban areas and barren land. Therefore, this study does not quantify the actual carbon emissions within the built-up areas. However, this study quantifies the overall impact of COVID-19 related activities on carbon emissions in vegetated and/or partially vegetated areas within built-up areas.

In the future, it is recommended to compare carbon emissions for quarterly and half-yearly periods to quantify the change in carbon emissions among pre-COVID, COVID, and post-COVID years. Further, it is recommended to include all types, lengths, and degrees of measures adopted during the pandemic to compare carbon emissions in major cities and countries.

Data availability

All data generated or analyzed during this study will be available upon request.

SMAP Net Ecosystem Exchange (NEE) from NASA Earth Data https://search.earthdata.nasa.gov/search, and National Snow and Ice Data Center (NSIDC0) https://nsidc.org/data/SPL4CMDL.

CRediT authorship contribution statement

R.L.R., and V.P.S. developed this concept and designed the research, S.K.S. and B.S.A contributed in methodology and discussion of this manuscript, Y.H. contributed to data collection and analysis, R.L.R., V.P.S., S.K.S., and B.S.A. contributed to paper writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.151503.

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